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Deposited in DRO:

15 May 2017

Version of attached file:

Accepted Version

Peer-review status of attached file:

Peer-reviewed

Citation for published item:

Llorca, M. and Jamasb, T. (2017) 'Energy efficiency and rebound effect in European road freight transport.', *Transportation research. Part A, policy and practice.*, 101 . pp. 98-110.

Further information on publisher's website:

<https://doi.org/10.1016/j.tra.2017.05.002>

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ENERGY EFFICIENCY AND REBOUND EFFECT IN EUROPEAN ROAD FREIGHT TRANSPORT

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26 February 2017

Abstract

Energy efficiency has become a primary energy policy goal in Europe and many countries and has conditioned the policies towards energy-intensive sectors such as road freight transport. However, energy efficiency improvements can lead to changes in the demand for energy services that offset some of the achieved energy savings in the form of rebound effects. Consequently, forecasts of energy savings can be overstated. This paper analyses the energy efficiency and rebound effects for road freight transport in 15 European countries during the 1992-2012 period. We use a recent methodology to estimate an energy demand function using a stochastic frontier analysis approach and examine the influence of key features of rebound effect in the road freight transport sector. We obtain, on average, a fuel efficiency of 89% and a rebound effect of 4%. Our results indicate that the achieved energy efficiencies are retained to a large extent. We also find, among other results, that the rebound effect is higher in countries with higher fuel efficiency and better quality of logistics. Finally, a simulation analysis shows significant environmental externalities costs even in countries with lower rebound effect.

Keywords: European road freight transport; stochastic frontier analysis; energy efficiency; rebound effect.

JEL Classification: C5, Q4, Q5, R4

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Acknowledgement: The authors acknowledge the support from the UK Engineering and Physical Sciences Research Council (EPSRC) for Centre for Sustainable Road Freight Transport (Project No. EP/K00915X/1).

1. Introduction

In recent decades there has been an increasing interest in adoption of energy and environmental policies that stimulate energy consumption reduction. The main goals of these policies are to reduce dependence on fossil fuels and mitigate the emissions of pollutants and Greenhouse Gas (GHG) emissions. This has in particular been the case for energy-intensive sectors such as transportation. In 2010, freight transport accounted for about 43% of global energy use in transport, which in turn represented 12% of total energy consumption and 10% of energy-related CO₂ emissions (IPCC, 2014). Moreover, the amount of fuel used by the trucking industry is expected to rise in the US and the EU (Léonardi and Baumgartner, 2004; IEA, 2010; De Borger and Mulalic, 2012), where trucks and vans emit 67% of the GHG emissions associated with transport (McKinnon, 2015).

A major means to tackle these issues has been to promote energy efficiency. Different countries have adopted different targets and policies to achieve energy and environmental objectives. In the European Union, where transport accounts for 25% of energy-related GHG emissions (Walnum *et al.* 2014), the European Commission has passed specific directives for the sector. Since the introduction of the Council Directive 88/77/EEC in 1988 and followed by other legislation, the implementation of ‘Euro’ Standards and the 2001 White Paper on transport, the energy consumption reduction objective have been partially achieved. The objective has been to reduce GHG emissions by 80-95% below the 1990 levels by 2050. The Commission recognises that the specific targets for the transport sector need to be adjusted downwards to 60% due to the complexity of this sector (European Commission, 2011; Walnum *et al.* 2014). The development and deployment of new and more efficient technologies remain one of the main strategies to achieve these objectives.

Broadly, energy efficiency improvement can be viewed as a reduction in energy use while the same level of demand for energy services is maintained and the comfort and quality of life are not reduced.¹ When energy savings are estimated based on potential energy efficiency enhancements, it is normally assumed that the demand for energy services remains the same. However, as these improvements also imply a reduction in the marginal cost of a given level of service, they may also lead to some increase in demand for energy services. This increase in energy consumption can, partially or totally, offset the initial expected

¹ Sustainability and environmental issues can also be incorporated into this broad definition.

savings. This phenomenon, or the so-called rebound effect, is normally overlooked in energy demand forecasts and design of energy and environmental policies.² If the magnitude of this effect is non-negligible, policies to reduce energy consumption through promotion of energy efficiency may not be fully effective.

Some researchers consider rebound effect as a natural adjustment to changing economic factors. Borenstein (2015) states that rebound effect can be considered as a reoptimisation process in response to variations of price and income. This means that rebound effect can be treated as welfare improvement in standard economic analysis. It should be noted that in order to assess the net effect of rebound effect on the overall welfare, the external costs generated by this phenomenon should also be incorporated in the analysis.

There is a large and diverse literature on rebound effect that analyse a broad range of countries, economic sectors using alternative definitions and measures. In the case of the transport sector, most estimates of rebound effects are in the range of 10 to 30% (see, e.g., Sorrell, 2007; Hymel *et al.*, 2010), though large estimates have also been obtained both in the short and the long run.

Rebound effect is also relevant in road freight transport. Maxwell *et al.* (2011) state that fuel efficiency improvement reduces the cost of freight transport which in turn make transportation cost efficient for more goods, for longer distances and with more frequency. This implies that fuel consumption could be reduced less than expected as a result of energy efficiency improvement. However, due to the lack of empirical studies and limited understanding of rebound effect in this sector, further research is needed (Winebrake *et al.*, 2012, 2015a, 2015b). Measuring rebound effect in road freight is also relevant from a policy perspective to assess the effect of energy efficiency improvements and national and international energy and climate change policies (Geller *et al.*, 2006; Barker *et al.*, 2007).

This paper aims to partially contribute to fill this gap in the literature by carrying out an empirical analysis of energy efficiency and rebound effect in the road freight transport of 15 European countries for the period 1992-2012. We use a recent econometric approach based on the estimation of Stochastic Frontier Analysis (SFA) models to estimate energy demand frontier functions. Through explicit modelling of energy efficiency, this approach

² There are, however, some exceptions in where rebound effects are considered by policy-makers. One example is in the evaluation of the voluntary agreement package by the British Department of Transport (DfT, 2005). The existence of rebound effect (labelled as “comfort taking”) is recognised and calculated in this evaluation and incorporated in their macroeconomic models. Nevertheless, rebound effect has not been generally considered as a “self-consistent political issue” (Gloger, 2011) in many countries.

allows us to obtain separate energy efficiency and rebound effect for each year of the study period and the countries analysed. Moreover, this method allows us to examine the determinants of rebound effect in the sector. The main contributions of the paper are in the application of the new methodology and the novelty of the sector analysed.

The paper is organised as follows. Section 2 provides a brief review of the literature on the demand for energy in road freight transport and the rebound effect. Section 3 describes the methodology and the specification of the energy demand function to be estimated. Section 4 presents the data used in the empirical analysis, reports the parameter estimates and presents the results obtained from those estimates. Section 5 is conclusions.

2. Energy demand and rebound effect in road freight

The demand for road fuel is a derived demand for energy services in road transport. In essence this implies that there is a demand for transporting goods and people that is to be satisfied through a combination of capital, labour and fuel. There is an extensive body of literature on the economics of transport in which the demand for fuel is modelled through a range of approaches such as econometric techniques, artificial intelligence approximations, multi-criteria analysis or simulation methods (see, e.g., Limanond *et al.*, 2011; or Suganthi and Samuel, 2012).

Among the econometric approaches, Llorca *et al.* (2017) propose modelling the demand for fuel in the transport sector in Latin American and Caribbean countries through the estimation of several SFA models. This approach was proposed by Filippini and Hunt (2011) to estimate aggregate energy frontier demands and allows obtaining measures of the energy efficiency of specific sectors or for the whole economy.³ In this framework fuel is considered an input factor that is used in combination with other inputs to produce energy services. According to Filippini and Orea (2014) aggregate energy demand frontier functions can be understood as reduced-forms of underlying structural models that are based on utility optimising problems. This approach has recently been extended by Orea *et al.* (2015) to obtain not only indicators of the level of efficiency in the use of energy but also to measure the rebound effect associated with improvements in energy efficiency.

³ The use of this type of approach has become common in recent years (see, Evans *et al.*, 2013; Filippini and Hunt, 2011, 2012, 2015a, 2015b; Filippini and Zhang, 2016; Filippini *et al.*, 2014; Llorca *et al.*, 2017; Lundgren *et al.*, 2016; and Orea *et al.*, 2015).

Rebound effect as a concept and in relation to energy efficiency has attracted increasing attention during recent decades. Since Jevons (1865) suggested the concept of rebound effect, it has been analysed in diverse countries and sectors of the economy through the application of different empirical approaches. There are different classifications of rebound effect that can be analysed from the perspective of both consumers and producers. Although the theoretical arguments and the existence of the rebound effect are widely accepted, it is subject to extensive debate due to different conceptual perspectives. Empirical research offers a range of definitions, methodologies and consequently different estimates of the rebound effect.

The literature frequently distinguishes at least three types of rebound effects (see, e.g., Greening *et al.*, 2000; Sorrell and Dimitropoulos, 2008) namely, direct, indirect and economy-wide rebound effects. The *direct rebound* effect suggests that an improvement in energy efficiency for a particular energy service decreases the effective price of that service and provides incentives to increase the demand for that service. This reaction then offsets the expected energy savings that could be attributed to energy efficiency improvement. The *indirect rebound* effect arises from the abovementioned energy savings when they are reverted into demand for other goods and services that require energy for their provision. The *economy-wide rebound* effect relates to the reduction in the price of intermediate and final goods in the economy due to the decrease of real price of energy services. This results in an adjustment of the prices and quantities of goods and services consumed in the economy. These adjustments create a bias towards the consumption of the goods in those more energy intensive sectors, which may then yield an increase in energy consumption.

The rebound effect is generally measured as potential energy savings that are not finally achieved and normally takes values between 0 (zero rebound effect) and 100% (full rebound effect). However, rebound effect can also take values larger than 100%, labelled as backfire in the literature (Saunders, 1992) which means that improvements in energy efficiency can lead to increase energy consumption. The opposite case, which can seem counterintuitive, is labelled as super-conservation (Saunders, 2008) and represents a reduction in energy consumption that exceeds the expected savings.

Recent research has focused on the analytical definitions of the rebound effect in terms of different elasticities (see, e.g., a survey by the International Risk Governance Council, IRGC, 2013). The results for rebound effect in the transport sector range between 4 and 87% in the short run and between 5 and 66% in the long run. However, most of the

results for this sector are between 10 and 30% (see, e.g., Sorrell, 2007; Hymel *et al.*, 2010). This wide range of results is a consequence of the differences in the definitions of the rebound effect, the type of approaches applied, the countries analysed and the level of aggregation in the data used.

The original definition of the rebound effect from Khazzoom (1980) was in relation to efficiency elasticities of demand for energy services. However, this type of elasticities is not often estimated. Instead, price elasticities of demand for energy have frequently been econometrically estimated and used as proxies of the rebound effect.⁴ The vast majority of studies assume that the response to changes in fuel price is equal to the response in changes of fuel efficiency. Hanly *et al.* (2002) showed that for the case of transport, this approach is likely to overestimate the rebound effect due to the endogeneity between energy prices and efficiency choice. It should be noted that some researchers view elasticities of energy services as not being a good measure of rebound effect and therefore price-induced energy efficiency should be taken into account (Saunders, 2000; Jenkins *et al.*, 2011).

Ignoring rebound effects can lead to overstating the benefits of energy efficiency policy measures, which can in turn lead to decisions such as the (over)allocation of public funds to ineffective environmental and energy policies. Policy makers may need to take rebound effect into account for air quality, energy security, and climate change policy reasons. A rebound effect different from zero implies that the expected proportional reductions in emissions from fuel efficiency improvements might not be achieved. Therefore, the policy goals to reach specific levels of emissions through fuel efficiency enhancements might need to be adjusted accordingly in order to compensate this effect. Nonetheless, as it has been remarked (Jägerbrand *et al.*, 2014; Wang and Lu, 2014), there is little research on rebound effect in road freight in spite of the need to assess the effectiveness of the policies applied to reduce fuel consumption in this sector (Small and Van Dender, 2007).

In their survey, Jägerbrand *et al.* (2014) find that rebound effects on road freight transport are estimated to be between 13 and 36.5% in the short run and between 12 and 45% in the long run. Ruzzenenti and Basosi (2008) find an increase in the energy efficiency of road freight transport in Europe of 40% between the second half of the 1970's to the first half of the 1990's. The study proposes the use of a theoretical framework taken from thermodynamics and evolution in conjunction with a traditional economic approach to

⁴ An alternative method that has been frequently used is general equilibrium modelling.

explain the rebound effect. Their main argument is that the complexity of the system counterbalances the positive effect of a high efficiency.

Anson and Turner (2009) use a Computable General Equilibrium (CGE) model to obtain economy-wide measures of oil rebound effect from energy efficiency improvements in the Scottish commercial transport industry. They find a rebound effect of 36.4% in the short run and 39.2% in the long run for the sector. At economy-wide level they find a rebound effect of 36.5% in the short run and 38.3% in the long run. They also find a disinvestment effect which implies that in most cases the rebound effect in the long run is constrained by a disinvestment that reduces the productive capacity in the energy sectors. These authors highlight the work of Gately (1990) in which fuel price elasticity of Heavy Goods Vehicle (HGV) transport in the US is estimated through an econometric analysis and finds a price elasticity of -0.37 which should be equivalent to a direct rebound effect of 37%. Graham and Glaister (2002) conducted an international survey on road traffic and fuel demand observing the freight traffic elasticities in different papers. These elasticities frequently lie between -0.4 and -0.8 that are equivalents to rebound effects between 40 and 80%.

Matos and Silva (2011) estimate the demand for road freight transport in Portugal using a two-stage least squares model. They use aggregate time series data for the period 1987-2006. The study pays attention to the changes in the energy cost of transport while they also correct for the endogeneity of the price variable. They show that a large share of the operating costs in road freight industry depends on energy consumption, and an increase in fuel efficiency that reduces these costs will result in a significant increase in demand for energy services. They estimate the rebound effect to be approximately 24%.

De Borger and Mulalic (2012) analyse fuel use in the trucking industry of Denmark for the period 1980-2007 using aggregate time series data. Using a simultaneous equations model they find a rebound effect of 10% in the short run and 17% in the long run. Moreover, they find that higher fuel prices increase the average capacity of trucks. This feature also leads the firms to invest in new and more efficient trucks. The joint influence of their findings make that the effect of an increase in fuel prices on fuel use is not very relevant. The study estimates the short run and long run price elasticities to be -0.13 and -0.22 respectively. They also find a reduction in the realised energy efficiency of the trucking industry in Denmark. The study justifies this reduction as being partially due to rising congestion and 'Just-in-Time' behaviour of firms, which also is a consequence of the reduction in the utilisation of vehicle capacity.

Winebrake *et al.* (2012) discuss the terminology and theory of rebound effect and conduct a survey of empirical papers that include information on the rebound effect of Heavy Duty Vehicles (HDV). The survey finds that no study has analysed the changes in demand for energy or energy services with respect to changes in energy efficiency. They provide some rebound effects based on the estimations of the elasticity energy price services providing differences between the short- and long-run adjustments. The authors highlight the studies by the US National Highway Traffic Safety Administration (EPA, NHTSA, 2011a, 2011b) in the elaboration of the rulemaking to establish GHG emissions and fuel efficiency standards for medium and HDVs. They obtain rebound effects between 13 and 22% in the short run and between 12 and 45% for the long run.

More recently, Winebrake *et al.* (2015a, 2015b) estimate fuel price elasticities for single-unit truck operations and combination trucking sector in the US. They apply first-difference and error correction models to time series data for the periods 1980-2012 and 1970-2012 respectively. The authors state that their estimates may, under certain assumptions, be used as a proxy for rebound effect. In general they find fuel price elasticities that are not statistically different from zero, although in the case of combination trucking sector this happens since the deregulation of the sector in 1980. They offer some possible explanations for their finding such as the lack of incentives for firms to reduce travel or fuel consumption, adjustments in other modifiable operational costs, the “principal-agent” problem or the nature of freight transportation.

Wang and Lu (2014) use a double logarithmic regression equation and an error correction model to analyse the direct rebound effect in the short run and long run of different regions of China from 1999 to 2011. They find a partial rebound effect in the long run between 52 to 84%. This implies that a large share of the expected reduction in energy demand could not be achieved and the policies indented to improve energy efficiency are not effective. Nevertheless, they find evidence of a slight super conservation effect in the short run.

Borenstein (2015) argues that there are three strands of research in the energy efficiency literature. The first focuses on measuring the direct energy savings derived from specific investments, the second analyses the rebound effect and the third attempts to estimate the welfare impacts from the quantitative findings in the other two strands. The present paper is in the second type of analyses. We use the approach recently proposed by Orea *et al.* (2015) and apply this to estimate rebound effect and fuel efficiency in the road freight

transport for the European countries and years analysed. The results are of direct policy relevance given that fuel efficiency standards are among the main policy regulations to reduce environmental effects in the commercial transport sector and especially for heavy duty trucks (Maxwell *et al.* 2011). In order to assess the consequences of fuel economy regulation, information about the rebound effect should be based on analysing data series of different countries. If efficiency standards fail as pollution control tools, fuel taxes should maintain a prominent role in climate policies in addition to other measures (Fronzel *et al.*, 2012).

3. Methodology

Several empirical approaches, mostly based on estimates of energy price elasticities, have been applied to measure rebound effect in the literature. These studies rely on the assumptions that consumers respond to an increase (decrease) in energy efficiency and a decrease (increase) in energy price has the same magnitude of effect. However, this implicit estimation of rebound effect can be flawed in many cases. Sorrell and Dimitropoulos (2008) indicate that this approach may produce biased estimates if energy efficiency is not adequately controlled. Moreover, it should be noted that, in general, what is estimated is a unique elasticity that represents the rebound effect on the sample average. As a result, varying rebound effects across individuals and over time are generally not considered in these models.

In this paper, we adopt the method proposed by Orea *et al.* (2015) that is based on the application of an SFA technique to obtain a direct measure of rebound effect through estimating energy demand functions. In this approach energy efficiency is explicitly modelled and the rebound effect is an adjustment factor that augments or diminishes the influence of variations in efficiency over energy consumption. Therefore, it allows distinguishing between the consequences of changes in energy price and energy efficiency. One of the main advantages of this method is that energy efficiency and rebound effect are identified at observation level which means that both measures can be estimated per country and year. Thus, this permits to analyse the evolution of these magnitudes over time for each country. Moreover, Orea *et al.* (2015) find that the estimated efficiencies and rebound effects are robust across alternative specifications of technical progress in the frontier. Although it was

an empirical evidence, this may be a relevant property of the approach if it is found that this circumstance is maintained for other applications.⁵

That approach aims to estimate a stochastic energy demand frontier similar to the one proposed by Filippini and Hunt (2011). The original model can be presented in logarithmic form as:

$$\ln Q = \ln f(Y, P, X, \beta) + v + u \quad (1)$$

where Q is the aggregate fuel consumption in road freight transport, Y is the GDP, P is the price of fuel in the sector, X is a set of control variables, β are the parameters in the frontier to be estimated, v is a noise term that follows a normal distribution and u is the level of underlying inefficiency and can vary across countries and over time. Following the conventional SFA literature that started with the seminal paper of Aigner *et al.* (1977) (ALS henceforth), it is often assumed that this term follows a positive half-normal distribution, i.e. $u \sim N^+(0, \sigma_u^2)$.

Unlike other approaches where energy efficiency is frequently defined as the energy required per unit of output of useful work, in this approach, based on the conditional mean of the inefficiency term proposed by Jondrow *et al.* (1982), the level of energy efficiency can be expressed as:

$$E_{it} = Q_{it}^* / Q_{it} = \exp(-\hat{u}_{it}) \quad (2)$$

where Q_{it}^* represents the aggregate fuel demand in country i in period t on the frontier, i.e., the minimum level of fuel necessary for this economy to produce its output level in the sector, Q_{it} is the actual aggregate fuel consumption observed in this country, and E_{it} is thus a measure of efficiency bounded between zero and unity. The difference between 1 and this measure of inefficiency shows the amount of energy consumption that could be reduced in this country (expressed as a decimal fraction) while maintaining the same level of transport services.

The model proposed by Orea *et al.* (2015) is an extension of the model in Equation (1). They note that this model implicitly imposes a rebound effect which is equal to zero. Following Saunders (2000) the rebound effect can be expressed as $R = 1 + \varepsilon_E$, where ε_E represents the elasticity of energy demand with respect to the changes in energy efficiency,

⁵ In fact, we observe the same feature in our application. This issue is commented on in Section 4.

i.e. $\varepsilon_E = \partial \ln Q / \partial \ln E$. From Equation (2) we can infer that $\ln E = -u$ and hence the implicit energy efficiency elasticity in Equation (1) is -1, which in effect is synonymous to assuming that the rebound effect is zero. It is evident from Equation (1) that an increase in energy efficiency (i.e. a decrease in u) will be fully translated into a reduction in fuel consumption, Q .

In order to account for the likely effect of a rebound effect, Orea *et al.* (2015) propose an energy demand frontier model based on the following specification:

$$\ln Q = \ln f(Y, P, X, \beta) + v + [1 - R(\gamma'Z)]u \quad (3)$$

where $u = -\ln E \geq 0$ and represents the level of ‘underlying energy inefficiency’. In this model the final effect of changes in efficiency over fuel consumption does not imply proportional reductions in fuel consumption as these variations are adjusted by R , labelled as the rebound-effect function. This function is not observed by the researcher, but it is linked to the demand for energy services and is approximated with a set of determinants, Z , such as income and price of energy services. γ is the set of parameters to be estimated within the rebound-effect function.⁶

There are two noteworthy aspects in this model. First, if the rebound-effect function does not depend on any covariate, the model collapses to the basic stochastic frontier demand model presented in Equation (1) and suggested by Filippini and Hunt (2011) that imposes zero rebound effects. If the rebound effect varies across observations, this model would allow us to obtain both time- and country-specific rebound effects that can then be used for further analyses.

Second, the choice of a particular functional form of the rebound-effect functions is constrained in this setting both by methodological and practical issues.⁷ Orea *et al.* (2015) suggest two simple functional forms for the rebound-effect function that are based on the exponential function. Moreover, they propose a strategy to solve the identification problem that arises in this approach to estimate the intercept of the rebound-effect function. In this paper we use their proposed specification to obtain a measure of the partial rebound effect

⁶ This model and the ALS model presented in Equation (1) are estimated by maximum likelihood. For more details about the estimation procedure, the identification of the parameters and the computation of energy efficiencies and rebound effects, see the Appendix in Orea *et al.* (2015).

⁷ The second error term in Equation (3), i.e. $[1 - R(\gamma'Z)]u$, is a one-sided distribution that is positive in order to distinguish inefficiency from noise. This circumstance imposes that both the energy efficiency elasticity, i.e. $(1 - R)$, and u are positive and hence, by implication, the rebound effect is always smaller than unity.

(i.e. $0 < R < 1$) and the strategy based on the estimation of the ALS model to adjust the estimated intercept in the rebound-effect function.⁸

If we consider a translog specification for the frontier demand for fuel, the final model to be estimated can be expressed as:⁹

$$\ln Q_{it} = \alpha_i + \delta_t + \sum_{p=1}^P \beta_p \ln X_{pit} + \frac{1}{2} \sum_{p=1}^P \sum_{r=1}^P \beta_{pr} \ln X_{pit} \ln X_{rit} + v_{it} + \left(1 - \frac{e^{\gamma_0 + \sum_{s=1}^S \gamma_s \ln Z_{sit}}}{1 + e^{\gamma_0 + \sum_{s=1}^S \gamma_s \ln Z_{sit}}} \right) u_{it} \quad (4)$$

where X stands now for all the variables in the frontier demand for fuel, α_i represents country-specific intercepts, δ_t is a set of time dummy variables and other variables and parameters are defined as above.

4. Data and results

We use an unbalanced panel data set with information about road freight transport in 15 European countries for the period 1992-2012.¹⁰ The dependent variable in our model is the aggregate of fuel consumption from trucks and light vehicles in the road freight transport sector that is predominantly formed by diesel (which also includes biodiesel and bioethanol) and gasoline.¹¹ This information has been obtained from the data provided by the Odyssee-Mure Project and Enerdata.

We obtained information about prices of diesel (for commercial use) and various types of gasoline at country level from the reports on “Energy prices and taxes” from the IEA (2007, 2014).¹² We construct a transitive multilateral price index to aggregate the price of diesel and gasoline to be incorporated in our model. Unlike standard price indices such as

⁸ This model is labelled as PA model in Orea *et al.* (2015). We have also estimated the SC model here, but it is rejected against the PA model in our application. For more details about these models, see Orea *et al.* (2015).

⁹ The more restricted Cobb-Douglas specification is rejected in favour of the translog specification in our model.

¹⁰ The list of European countries includes: Austria, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Netherlands, Poland, Slovenia, Spain, Sweden and United Kingdom. It should be noted that this sample of countries accounts for about 90% of the EU-28's GDP during the sample period.

¹¹ The vast majority of HGVs run on diesel. However, as our sample also includes light duty vehicles, we have also included the gasoline consumption. Other fuels such as LNG (Liquefied Natural Gas), CNG (Compressed Natural Gas) or electricity are not at present widespread as alternatives that need to be considered here.

¹² We could not obtain historic data about biofuels prices. We are aware that some countries have applied specific measures to favour the use of biofuels (e.g., tax rebates in the case of the UK). As a consequence of this shortcoming, we have assumed the same prices both for diesel and biofuels. It should be remarked, however, that the share of biofuels in our sample is practically negligible, thus we believe this issue does not imply a distortion in our results.

Paasche or Laspeyres, this type of index does not impose a base year for each country and allows a consistent comparison across countries over time. The index used here is similar to that proposed by Caves *et al.* (1982) to obtain transitive Törnqvist indices. This procedure is based on the method suggested by Elteto and Koves (1964) and Szulc (1964). The idea behind the calculation of this index is that the “comparison between two firms (countries) is obtained by first comparing each firm (country) with the average firm (country) and then comparing the differences in firm (country) levels relative to the average firm (country)” (Coelli *et al.*, 2005, p. 117).

A variable that is also included in the model is country GDP which is measured in millions of 2005 US dollars at Purchasing Power Parity (PPP). This variable along with the information on the road freight transport were obtained from the statistical information provided by the Organisation for Economic Co-operation and Development (OECD). Additionally we collected information on the stock of trucks and light vehicles, and rail goods traffic from the Odyssee-Mure Project and Enerdata. Another variable included is the Logistics Performance Index constructed by The World Bank based on six dimensions of trade: customs performance, infrastructure quality, ease of shipment, logistics of services, ease of tracking and timeliness.¹³ Table 1 presents the descriptive statistics of the variables used in the analysis.

Table 1. Descriptive statistics

<i>Variable</i>	<i>Description</i>	<i>Units</i>	<i>Mean</i>	<i>Std. Dev.</i>	<i>Min.</i>	<i>Max.</i>
<i>Q</i>	Total fuel consumption	Mtoe	6.03	5.58	0.32	18.36
<i>Qd</i>	Diesel consumption	Mtoe	5.58	5.30	0.21	17.18
<i>Qg</i>	Gasoline consumption	Mtoe	0.45	0.52	0.01	2.08
<i>Pd</i>	Price of diesel	USD/litre	0.99	0.40	0.33	2.44
<i>Pg</i>	Price of gasoline	USD/litre	1.36	0.46	0.59	3.01
<i>P</i>	Transitive multilateral price index	Index	189.43	76.12	66.02	461.77
<i>GDP</i>	Gross Domestic Product	Mill. 2005 USD	837,91	806,79	47,79	2,929,94
<i>Stock_T</i>	Stock of trucks	Mill.	0.36	0.38	0.02	1.49
<i>Stock_LV</i>	Stock of light vehicles	Mill.	1.50	1.49	0.05	5.91
<i>Stock_TLV</i>	Stock of trucks and light vehicles	Mill.	1.86	1.75	0.07	6.47
<i>RFT</i>	Road Freight Transport	Mill. tonne-km	90,398	88,491	1,849	343,439
<i>RaGT</i>	Rail Goods Traffic	Gigatonne-km	22.44	24.76	0.29	115.65
<i>LPI</i>	Logistics Performance Index	Index	3.69	0.33	3.09	4.09

¹³ This index evaluates 160 countries and has been calculated using statistical techniques for different years, 2007, 2010, 2012 and 2014. In this paper we use an average of these four values per country and added as a time-invariant variable in the rebound-effect function of the estimated energy demand.

Figure 1 shows fuel use per unit of activity in road freight transport sector, i.e. tonne-km. This ratio is an energy intensity indicator that is frequently viewed as a proxy for the energy efficiency. We can see from this indicator that energy efficiency improvement has been a relevant factor in recent decades. In contrast there has been a continuous growth in demand for energy services in the sector per unit of GDP. This trend could be the result of increasing demand from business and consumers (e.g., e-commerce or Just-in-Time manufacturing) that, as stressed by Holguín-Veras and Thorson (2003), has clashed with the pressure of communities to reduce the environmental impact of transport activities. Sorrell *et al.* (2009) also suggest that this trend in payload weight can produce continued inefficiencies in the use of vehicles that could be caused by volume constraint bindings applied before weight constraints.

Figure 1. Energy intensity and weight of road freight transport to GDP

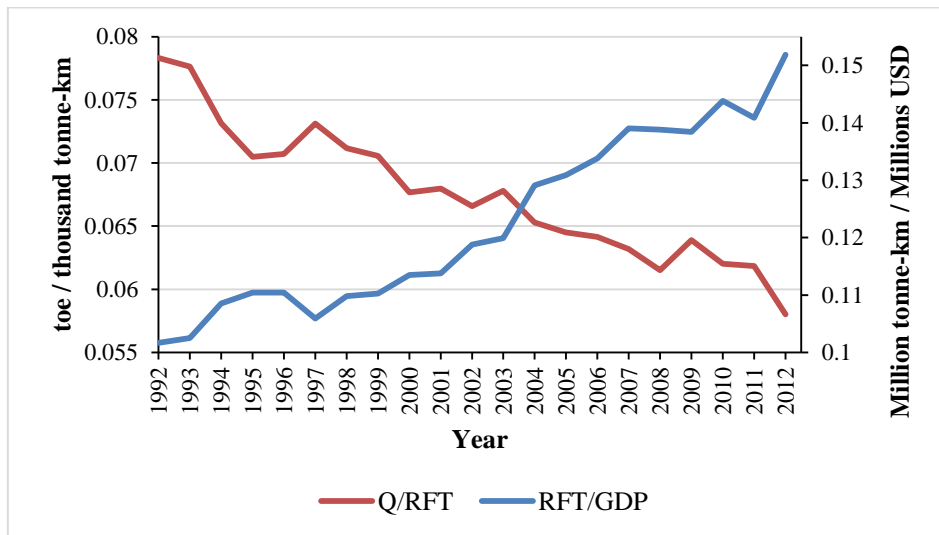


Table 2 shows the parameter estimates of the energy demand frontier models that will be used to analyse some selected features of this sector. We present the basic ALS frontier model that does not account for the rebound effect (or implicitly imposes a rebound effect equal to 0) and the extended model that incorporates the rebound-effect function that adjusts for the influence of changes in the energy efficiency on fuel consumption.

We observe that many of the coefficients of the variables in the frontier along with the parameters of the random term are not significant in the ALS model. This might be evidence of biased estimates due to the possible presence of heteroscedasticity (see Caudill and Ford, 1993) that is addressed in the extended model that incorporates the rebound-effect function.

On the other hand, in the rebound-effect model, all first-order coefficients of the variables in the frontier are significant and show the expected signs.¹⁴ It should be noted that these coefficients represent the values of the elasticities of the variables estimated at the sample mean. GDP has a positive sign indicating that higher income countries demand more fuel. As expected, the price index shows a negative sign when a demand function is estimated.¹⁵ We also incorporated the ratio of price of diesel and price of gasoline to reflect relative changes in the price of diesel with respect to changes in the price of gasoline. The positive sign of the coefficient indicates that an increase (decrease) in the price of diesel is compensated with an increase (decrease) in the overall consumption of fuel. This is plausible given that, for a given demand for energy services, the fuel requirement of gasoline engines is larger than that of diesel engines.

The above result may imply that there is a substitution effect as a result of changes in relative prices, with freight being transferred from gasoline vehicles to diesel vehicles (or vice versa). In our sample, trucks are overwhelmingly diesel, but we observe that the majority of light vehicles also have diesel engines especially in recent years. This trend in the dieselisation of light duty fleet can be observed in most European countries (Wadud, 2016). Diesel engines have become popular among light vehicles because of their robust design, superior fuel performance and ongoing technology improvements (Momenta, 2006). Moreover, there has been a tendency to build and use of bigger light vehicles with more load space that can be operated as substitutes of small HGVs (CfIT, 2010). Allen *et al.* (2016) show that in the case of London, the share of HGVs has been relatively stable over the years, while light vehicles have grown exponentially, which reflects a transition of freight transport from trucks to light vehicles. They present different reasons for this trend such as the relative lack of regulation governing light vehicle use compared to HGVs, the popularity of Just-in-Time deliveries, the growth in demand for express and parcels services or the impact of congestion. Therefore, changes in the relative prices of fuel may be an additional influence on the substitution of freight transport from HGVs to light vehicles.

¹⁴ The use of a translog specification implies that the energy demand elasticities vary from point to point. To test the monotonicity conditions under the translog specification we have carried out the Wald test. We only find statistically negative values for 4.27% of the observations in the case of the ratio of diesel and gasoline prices, and zero for GDP and the ratio of stock of light vehicles to trucks. In the case of fuel price we find no statistically significant positive elasticities. These results give us confidence about the fulfilment of the monotonicity conditions and the adequate properties of our estimated demand function.

¹⁵ It must be mentioned that the introduction of diesel prices and gasoline prices separately instead of the transitive multilateral price index means that one of the variables becomes positive because of collinearity issues. The degree of correlation of these variables is 96.63%.

Table 2. Parameter estimates of the energy demand frontier function
(These models include time and country dummy variables)

<i>Parameters</i>	ALS model		Rebound-effect model	
	<i>Est.</i>	<i>Est./s.e.</i>	<i>Est.</i>	<i>Est./s.e.</i>
<i>Frontier</i>				
Intercept	0.855	0.009	0.990 ***	8.066
$\ln \text{GDP}_{it}$	0.873 ***	6.400	0.839 ***	6.419
$\ln P_{it}$	-0.145	-1.142	-0.147 *	-1.885
$\ln (\text{Pd/Pg})_{it}$	0.440 **	2.356	0.188 **	2.100
$\ln (\text{Stock_LV/Stock_T})_{it}$	0.013	0.161	0.162 ***	3.636
$\frac{1}{2} (\ln \text{GDP}_{it})^2$	-0.032	-0.340	-0.114	-1.597
$\frac{1}{2} (\ln P_{it})^2$	0.894 ***	5.386	0.050	0.317
$\frac{1}{2} [\ln (\text{Pd/Pg})_{it}]^2$	-0.709	-0.400	-0.385	-0.477
$\frac{1}{2} [\ln (\text{Stock_LV/Stock_T})_{it}]^2$	-0.214	-1.167	-0.065	-0.729
$\ln \text{GDP}_{it} \cdot \ln P_{it}$	-0.024	-0.517	-0.003	-0.087
$\ln \text{GDP}_{it} \cdot \ln (\text{Pd/Pg})_{it}$	0.291 *	1.823	0.154 **	2.056
$\ln \text{GDP}_{it} \cdot \ln (\text{Stock_LV/Stock_T})_{it}$	-0.309 ***	-3.838	-0.094 *	-1.893
$\ln P_{it} \cdot \ln (\text{Pd/Pg})_{it}$	-0.541	-1.301	0.088	0.402
$\ln P_{it} \cdot \ln (\text{Stock_LV/Stock_T})_{it}$	-0.057	-0.646	-0.179 ***	-2.933
$\ln (\text{Pd/Pg})_{it} \cdot \ln (\text{Stock_LV/Stock_T})_{it}$	0.010	0.031	0.567 ***	3.412
<i>Noise term</i>				
$\ln (\sigma_v)$	-2.581	-0.319	-3.921 ***	-34.936
<i>Rebound-effect</i>				
Intercept			0.845 *	1.838
$\ln \text{GDP}_{1t}$			-0.794 ***	-2.940
$\ln \text{GDP}_{inc, it}$			-0.935	-0.502
$\ln \text{GDP}_{dec, it}$			2.738	0.545
$\ln P_{1t}$			-5.871 ***	-4.012
$\ln P_{inc, it}$			0.549	0.612
$\ln P_{dec, it}$			3.814 *	1.712
$\ln \text{RaGT}_{it}$			-0.380 **	-2.157
$\ln (\text{Stock_T/Stock_TLV})_{it}$			2.094 ***	3.355
$\ln \text{LPI}_i$			6.216 **	2.061
<i>Inefficiency term</i>				
$\ln (\sigma_u)$	-6.842	0.000		
Log-likelihood	326.637		421.606	

Significance code: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The ratio of light vehicles to trucks was added to control for the composition of the fleet of vehicles in each country.¹⁶ We obtain a positive coefficient for the variable, which seems to indicate that a higher proportion of light vehicles provides more substitution

¹⁶ Although it can be argued that these variables are themselves the result of endogenous choices driving the demand of energy, it should be noted that we can assume that the ratio of these variables is econometrically exogenous (for details see Coelli, 2000; or Kumbhakar, 2011). Therefore, their inclusion does not generate any econometric problem.

possibilities in the sector, thereby influencing fuel consumption because of gasoline engines used in some of them. Additionally, time dummies have been included in both models (not shown in the paper) and these show positive sign and a slightly increasing magnitude that reflects the growth in demand for fuel over time in this sector. We observe that the estimated energy efficiencies and rebound effects are robust across alternative specifications of the technical progress in the frontier, as highlighted by Orea *et al.* (2015). In our application, there is a correlation of 99.4% between the energy efficiencies and 95.2% between the rebound effects when the models with and without time dummies are compared. Finally, country-specific dummies (i.e. fixed effects) were added to control for unobserved heterogeneity.

Regarding the rebound-effect function, we have included the GDP, the transitive multilateral price index, the railway freight transport, the share of trucks with respect to total number of trucks and light vehicles in the sector and the Logistics Performance Index. The GDP and the fuel price are introduced by decomposing the original variables in three variables: (i) the value of the logarithm of the variable in the starting year, (ii) cumulative increases in the logarithm of the variable and (iii) cumulative decreases in the logarithm of the variable. This strategy allows us to examine the asymmetric effects of changes in the variables.¹⁷ The coefficients of most of the variables in the rebound-effect function are statistically significant. We find a negative coefficient for GDP that confirms the negative relationship between rebound effect and income as suggested by some authors (see, e.g., instance Greene, 1992). Nevertheless, this circumstance is only observed when the initial levels of each country are compared. Regarding fuel price, some authors maintain that failing to control for asymmetric responses to variations in fuel prices can result in biased estimates of the rebound effect (see, e.g., Frondel and Vance, 2013). In our model we obtain a negative coefficient for the initial levels of the variable and a positive coefficient for the cumulative decreases. The non-significance of the cumulative increases seems to indicate the presence of an asymmetric effect in the rebound effect with respect to changes in fuel price.

The negative coefficient for the railway freight transport can indicate that transport of goods by rail can be an alternative for some countries. Large values of rail goods traffic would have the consequence that higher fuel efficiency in road transport would generate a

¹⁷ This has been done in a similar fashion to previous papers in which aggregate energy and oil demand is analysed allowing for asymmetric responses respect to changes in price or income (see, e.g., Mork, 1989; Gately and Huntington, 2002; or Adeyemi and Hunt, 2007). It should be noted that the estimation of our model without taking into account the decomposition of the price and GDP variables leads to insignificance of both variables. Moreover, that model is rejected in favour of our preferred model that allows for asymmetric responses.

lower rebound effect. Although transportation of freight by rail can be viewed as an ‘unattractive mode’ (European Commission, 2011), the EU is promoting a shift to intermodal transport to achieve a sustainable freight transport (Tsamboulas *et al.*, 2007). It should be noted that improvements in fuel efficiency could also lead to modal substitution towards more polluting transport means (Walnum *et al.*, 2014). The expected savings could not be achieved if the rebound effect generates a higher modal share for road transport, for example through adoption of megatrucks (CER, 2014). As discussed by Winebrake *et al.* (2012), the effect of fuel economy improvements on alternative means of transport should be analysed to prevent unexpected modal shifts. In some Member States, rail transport already offers a service of quality and our estimates indicate that promotion of rail transport might be a suitable strategy to lessen the rebound effect in road freight transport.

Finally, the positive coefficient of the share of trucks reflects that the larger the percentage of trucks in the economy, the greater the fuel consumption. Therefore the benefits from a better fuel efficiency would be greater, which would enhance the rebound effect. The final variable included in the rebound-effect function is the Logistics Performance Index. The positive coefficient of this variable suggests that the rebound effect will be larger in countries with better infrastructure, easier shipment and in general better logistics. It can be argued that better logistic conditions facilitate an increase in demand for energy services in those countries. This seems to be in line with the view of Ruzzenenti and Basosi (2008) who remark that the complexity of the system counterbalances the positive effect of higher efficiency.

Regarding the values of the energy efficiency and the rebound effect, we find an average value of energy efficiency of 88.8% and a rebound effect of 3.8%.¹⁸ Figure 2 shows the evolution of the average value of the energy efficiency and the rebound effect over the period analysed. In both series we observe a similar trend, a decline of both measures during the first years of the sample and a slight recovery in the last years of the sample. This decline in fuel efficiency was also suggested by Piecyk and McKinnon (2010) in their scenario analysis of the carbon footprint of road freight transport. These authors suggest that a decline in fuel efficiency can occur due to the increased congestion or strict regulation over emissions. In relation to rebound effect, as stated by Walnum *et al.* (2014), there are several reasons for this phenomenon in road transport, such as a less efficient utilisation and routing

¹⁸ These average values are computed taking into account the size of each country. The road freight transport of each observation is used as a weighting variable for computation.

of vehicles, lower freight rates or induced demand due to lower charges for transport generated by the reduction in the shipping costs as a consequence of acquiring more fuel efficient vehicles.

Figure 2. Evolution of average efficiency and rebound effect

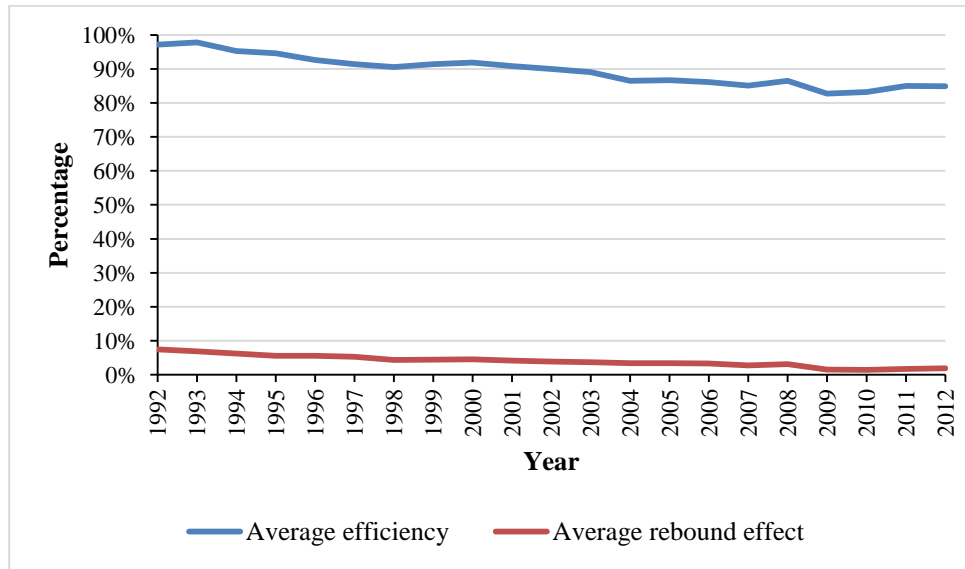


Figure 3 shows the values of both energy efficiency and rebound effect per country.¹⁹ We can take as an example of the reasonable magnitude of our results, the value of the rebound effect in Sweden, 7.9%. This value appears to be consistent with the findings of De Borger and Mulalic (2012), who estimated a rebound effect of 10% in the short run and 17% in the long run.²⁰ In general we obtain large rebound effects for more fuel efficient countries such as Austria, Germany or Denmark and low rebound effects close to 0% for countries with low energy efficiency scores such as Poland or Hungary.

As found by Orea *et al.* (2015) for the case of US residential energy demand, this result indicates that as fuel efficiency in road freight transport increases, the sector is less sensitive²¹ to changes in fuel efficiency and the reduction in fuel consumption is not as much as expected compared with less fuel efficient countries. Looking at our data we find that high fuel efficiencies are frequently associated with low demand for energy services in the sector per unit of GDP, but not necessarily to low consumptions per energy service. A decrease in

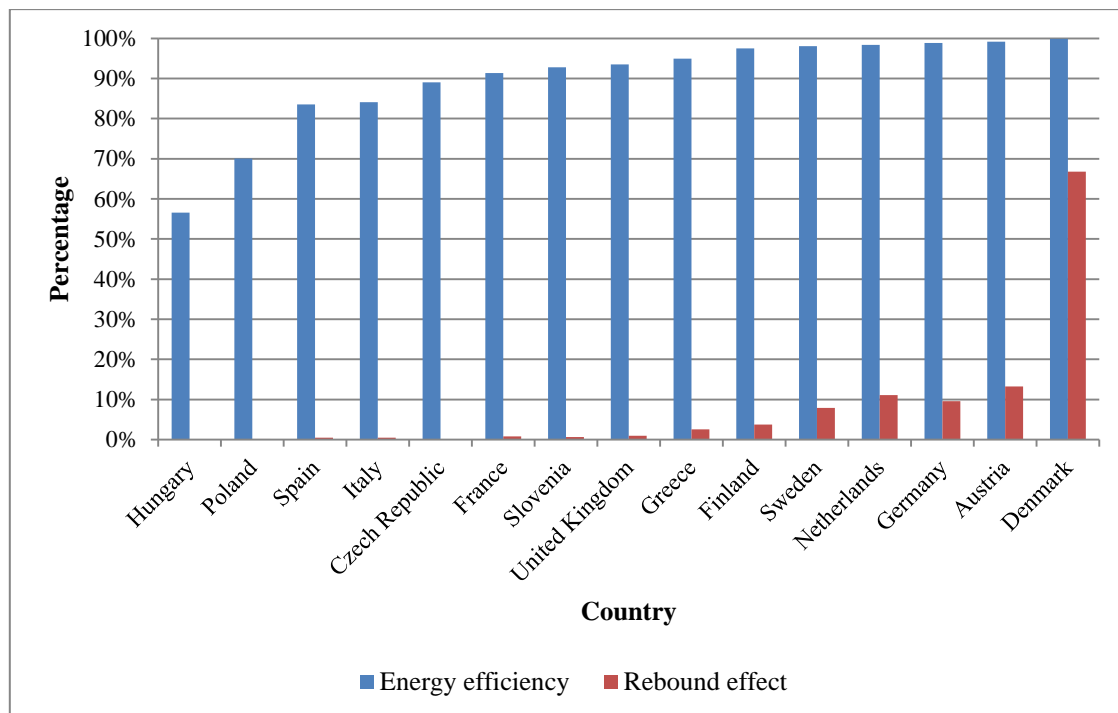
¹⁹ After the estimation of the model, both efficiency scores and rebound effects are computed at observation level. Figure 3 only shows the average value of these magnitudes per country.

²⁰ This comparison cannot be performed for the other countries in our sample due to the lack of previous empirical papers.

²¹ This refers to the energy efficiency elasticity of the demand for energy.

the marginal costs may generate incentives for providing energy services that initially were seen as not profitable, which in turn results in large rebound effects. Therefore, low fuel efficient countries could be viewed as priority objectives in energy and environmental policies, since improvements in fuel efficiency will likely produce large reductions in their fuel consumption and emissions.

Figure 3. Average efficiencies and rebound effects in each country



Finally, it is worth to recall that rebound effect simply reflects an increase in the demand for energy services induced by efficiency improvements. This means that the rebound effect is not undesirable *per se*. A rebound effect can imply an improvement in social welfare if the benefits of an increase in the demand for energy services surpass the externalities generated (Chan and Gillingham, 2015). Some studies recognise that rebound effect can be welfare enhancing if there are not external costs of large magnitude (see Hobbs, 1991; Borenstein, 2015; Gillingham *et al.*, 2014).

A crucial issue when analysing the rebound effect is its effect in terms of external costs (e.g., noise, air pollution or congestion). This cost should be internalised through charges in the use of infrastructures or vehicles. In that sense, the application of the so-called ‘Eurovignette directive’ can be viewed as a first step towards the internalisation of the costs

generated by HGVs. The internalisation of these external costs attributed to rebound effect should be a strategy to avoid the likely negative effect of the rebound effect. Although imposing taxes is generally not viewed as a desirable measure due to the distortive effects that they can generate, they can also be viewed as a tool that, combined with fuel efficiency improvements, can produce a positive effect on reducing the external costs from the rebound effect.

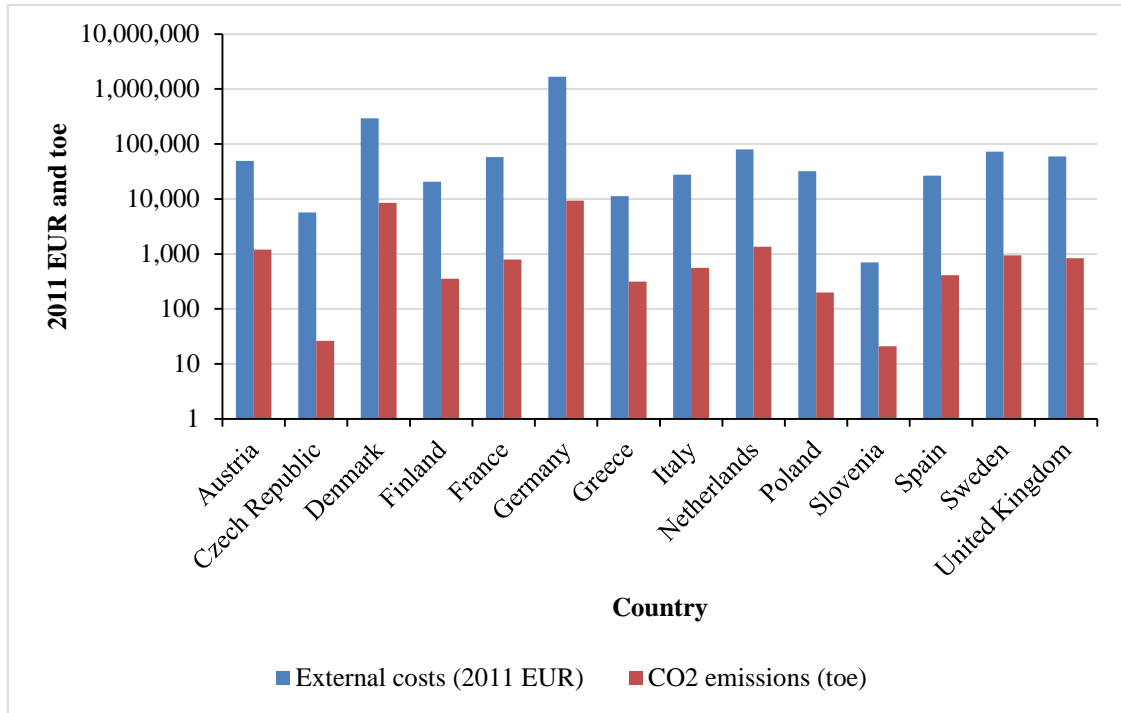
In order to examine the environmental impact of rebound effect in European countries, Figure 4 presents the results of a simulation exercise. The figure shows the effect of a 0.5% in energy efficiency improvement in the countries of our sample.²² The columns represent the external costs and CO₂ emissions from the rebound effect after energy efficiency enhancement in each country and should be incorporated to (partially) counterbalance the hypothetical forecast of externalities reduction. The information on the CO₂ emissions is obtained from the database of the Odyssee-Mure Project and Enerdata. The coefficients used to estimate the environmental costs were provided by the European Commission through the Marco Polo freight transport proposal (call 2011). These coefficients account for the environmental impact (air quality, noise and climate change) as well as the socio-economic impacts (accidents and congestion) of road freight transport activity in European countries.²³

We observe that, as expected, countries that show a large rebound effect also account for not achieving a large reduction in externalities after a fuel efficiency improvement. At the same time, countries such as France and the United Kingdom, despite showing a small rebound effect, present a significant decrease in CO₂ emissions and external costs not achieved after an efficiency improvement due to the large scale of the road freight sector in these countries. In particular, the case of Poland and Spain are notable. Although these countries are among those with the smallest rebound effect (and in the case of Spain it also shows one of the lowest external cost coefficients), they are among the countries in which the global CO₂ emissions and external cost reductions not achieved following a fuel efficiency enhancement are higher due to the large size of their road freight transport industry.

²² The results presented in Figure 4 are based on the simulated energy efficiency improvement (0.5%) along with the individual efficiency scores and rebound effects estimated for each of the countries in 2011. It should be clear that when we talk about external costs and CO₂ emissions in this simulation, we are not saying that fuel efficiency improvements lead to greater environmental impacts. Our results simply show the environmental impact attached to the rebound effect, i.e. the environmental impact reduction not achieved after the fuel efficiency enhancement.

²³ For more information about the computation of the coefficients see Brons and Christidis (2011).

Figure 4. Simulation of environmental emissions attributable to rebound effect after a 0.5% energy efficiency enhancement



Notes: This simulation is computed based on 2011 values.
Hungary is not included due to the lack of data for that year.

5. Conclusions

In the last few decades one of the main objectives of energy and climate policies has been the promotion of energy consumption reductions in energy-intensive sectors such as road freight transport. The aim of reducing energy consumption without distorting the freight traffic flows requires enhancement of fuel economy. However, such improvement implies a reduction in the marginal costs of energy service that in turn may incentivise an increase in its demand. This phenomenon, or the so-called rebound effect involves a growth in energy consumption that can partially or totally offset the expected energy efficiency gains. If the magnitude of this effect is not negligible, policies that aim to reduce energy consumption through the promotion of energy efficiency may not be fully effective. Rebound effect may also yield unexpected economic or environmental impacts, such as higher GHG emissions than expected. In this paper we have shown that while there is a broad theoretical and empirical literature on the rebound effect, this concept has not sufficiently been examined for the case of the road freight transport.

In order to fill this gap in the literature, we perform an empirical analysis of energy efficiency and rebound effect in the road freight transport industry of 15 European countries for the period 1992-2012. We apply a recent econometric approach based on estimation of SFA models to estimate an energy demand frontier function. Through explicit modelling of energy efficiency, this approach allows us to obtain estimates of both energy efficiency and rebound effect for road freight transport sector in each of the years and countries analysed. Moreover, this approach allows us to examine the influence of potential determinants of the rebound effect from which informed policy implications can be derived.

Our results show an average fuel efficiency of 88.8% and a rebound effect of 3.8% for the countries in the sample during the period. We find that both measures declined during the initial years of the sample and then slightly increased in the last years of the sample. We obtained large rebound effects for the countries that are more fuel efficient (e.g., Austria, Germany and Denmark) and low rebound effects for less fuel efficient countries (e.g., Hungary or Poland). Moreover, for some countries, the rebound effect reaches non-negligible values (up to 66.8%) which seem to justify the application of specific policies aimed to reduce rebound effect and not only enhancing energy efficiency. We showed that the share of trucks with respect to the total number of vehicles in the sector as well as the quality of logistics in the countries have an incremental effect on the rebound effect. On the other hand, the existence of a strong railway freight transport sector reduces the rebound effect.

Finally, we also examined through a simulation exercise that even in countries that exhibit low levels of rebound effect, the environmental impact reduction not achieved following an efficiency improvement can be significant due to the magnitude of the transport activity and the marginal cost of the externalities in those countries. From a European perspective, our results imply that extra benefits can be derived from policies encouraging fuel efficiency in those countries which are relatively fuel inefficient, not only because of the fuel efficiency improvement, but also because of their lower rebound effect. The rebound effect looks to be a potentially important issue and thus it is worthwhile to consider specific policies such as, for instance, cap-and-trade schemes to tackle it. Ideally, those policies should be combined with adequate price signals in the sector, i.e. the use of specific taxes, promotion of inter-modality and, where feasible, the provision of alternative and environmentally friendly means of transport, such as rail.

References

- Adeyemi, O.I. and Hunt, L.C. (2007), "Modelling OECD industrial energy demand: Asymmetric price responses and energy-saving technical change", *Energy Economics*, 29(4), 693-709.
- Aigner, D., Lovell, K. and Schmidt, P. (1977), "Formulation and estimation of stochastic frontier production function models", *Journal of Econometrics*, 6, 21-37.
- Allen, J., Piecyk, M. and Piotrowska, M. (2016), *An analysis of road freight in London and Britain: Traffic, activity and sustainability*, Report from the project "Freight Traffic Control 2050 (FTC2050): Transforming the energy demands of last-mile urban freight through collaborative logistics".
- Anson, S. and Turner, K. (2009), "Rebound and disinvestment effects in refined oil consumption and supply resulting from an increase in energy efficiency in the Scottish commercial transport sector", *Energy Policy*, 37, 3608-3620.
- Barker, T., Ekins, P. and Foxon, T. (2007), "Macroeconomic effects of efficiency policies for energy intensive industries: The case of the UK Climate Change Agreements, 2000-2010", *Energy Economics*, 29(5), 760-778.
- Borenstein, S. (2015), "A microeconomic framework for evaluating energy efficiency rebound and some implications", *The Energy Journal*, 36(1), 1-21.
- Brons, M. and Christidis, P. (2011), *External cost calculator for Marco Polo freight transport project proposals*, JRC Scientific and Technical report EUR 25010.
- Caudill S.B, and Ford J.M. (1993), "Biases in frontier estimation due to heteroscedasticity", *Economic Letters*, 41, 17-20.
- Caves, D.W., Christensen, L.R. and Diewert, W.E. (1982), "The economic theory of index numbers and the measurement of input, output, and productivity", *Econometrica*, 50(6), 1393-1414.
- CER (2014), *Megatrucks versus rail freight?*, Brochures from the Community of European Railway and Infrastructure Companies, Wednesday, 08 January 2014.
- Chan, N.W. and Gillingham, K. (2015), "The microeconomic theory of the rebound effect and its welfare implications", *Journal of the Association of Environmental and Resource Economists*, 2(1), 133-159.
- Coelli, T.J. (2000), *On the econometric estimation of the distance function representation of a production technology*, Discussion Paper 2000/42, Center for Operations Research and Econometrics, Université Catholique de Louvain, Belgium.
- Coelli, T.J., Rao, D.S.P., O'Donnell, C.J. and Battese, G.E. (2005), *An introduction to efficiency and productivity analysis*, 2nd ed. Springer, New York.
- Commission for Integrated Transport (2010), *Vans and the economy*, CfIT.

- De Borger, B. and Mulalic, I. (2012), “The determinants of fuel use in the trucking industry – volume, fleet characteristics and the rebound effect”, *Transport Policy*, 24, 284-295.
- DfT (2005), *Evaluation of the voluntary agreement package for the climate change programme review*, Department for Transport, London.
- Elteto, O. and Koves, P. (1964), “On a problem of index number computation relating to international comparison”, *Statistikai Szemle*, 42, 507-18.
- EPA, NHTSA (2011a), *Greenhouse gas emissions standards and fuel efficiency standards for medium- and heavy-duty engines and vehicles*, 76 FR 57106 (September 15, 2011).
- EPA, NHTSA (2011b), *Final rulemaking to establish greenhouse gas emissions standards and fuel efficiency standards for medium- and heavy-duty engines and vehicles: Regulatory impact analysis*, Washington, DC.
- European Commission (2011), *White paper on transport: Roadmap to a single European transport area - Towards a competitive and resource-efficient transport system*, European Commission, Luxembourg.
- Evans, J., Filippini, M. and Hunt, L.C. (2013), “The contribution of energy efficiency towards meeting CO₂ targets”, In: Fouquet, R. (Ed.) Edward Elgar, *Handbook of energy and climate change*, Cheltenham, UK and Northampton, MA, USA, 175-223 (Chapter 8).
- Filippini, M. and Hunt, L.C. (2011), “Energy demand and energy efficiency in the OECD countries: A stochastic demand frontier approach”, *The Energy Journal*, 32(2), 59-80.
- Filippini, M. and Hunt, L.C. (2012), “US residential energy demand and energy efficiency: A stochastic demand frontier approach”, *Energy Economics*, 34(5), 1484-1491.
- Filippini, M. and Hunt, L.C. (2015a), “Measurement of energy efficiency based on economic foundations”, *Energy Economics*, 52(S1), S5-S16.
- Filippini, M. and Hunt, L.C. (2015b), “Measuring persistent and transient energy efficiency in the US”, *Energy Efficiency*, 1-13.
- Filippini, M. and Orea, L. (2014), “Applications of the stochastic frontier approach in the analysis of energy issues”, *Economics and Business Letters*, 3(1), 35-42.
- Filippini, M. and Zhang, L. (2016), “Estimation of the energy efficiency in Chinese provinces”, *Energy Efficiency*, 1-14.
- Filippini, M., Hunt, L.C. and Zorić, J. (2014), “Impact of energy policy instruments on the estimated level of underlying energy efficiency in the EU residential sector”, *Energy Policy*, 69, 73-81.
- Fronzel, M., Ritter, N. and Vance, C. (2012), “Heterogeneity in the rebound effect: Further evidence for Germany”, *Energy Economics*, 34, 461-467.
- Fronzel, M. and Vance, C. (2013), “Re-identifying the rebound: What about asymmetry?”, *The Energy Journal*, 34(4), 43-54.

- Gately, D. (1990), "The US demand for highway travel and motorfuel", *The Energy Journal*, 11, 59-73.
- Gately, D. and Huntington, H.G. (2002), "The asymmetric effects of changes in price and income on energy and oil demand", *The Energy Journal*, 23(1), 19-55.
- Geller, H., Harrington, P., Rosenfeld, A.H., Tanishima, S. and Unander, F. (2006), "Policies for increasing energy efficiency: Thirty years of experience in OECD countries", *Energy Policy*, 34, 556-573.
- Gillingham, K., Rapson, D. and Wagner, G. (2014), *The rebound effect and energy efficiency policy*, Discussion Paper No. 14-39, Resources for the Future.
- Gloger, S. (2011), *Policies to overcome the rebound effect - A new challenge for environmental policy*, Report of the Ministry of Environment, Climate Protection and the Energy Sector, Baden-Wuerttemberg.
- Graham D.J. and Glaister, S. (2002), "The demand for automobile fuel: A survey of elasticities", *Journal of Transport Economics and Policy*, 36, 1-26.
- Greene, D. (1992), "Vehicle use and fuel economy: How big is the "rebound" effect?", *The Energy Journal*, 13, 117-143.
- Greening, L., Greene, D. and Difiglio, C. (2000), "Energy efficiency and consumption - The rebound effect - A survey", *Energy Policy*, 28, 389-401.
- Hanly, M., Dargay, J.M. and Goodwin, P.B. (2002) *Review of income and price elasticities in the demand for road traffic*. Final report to the DTLR under contract number PPAD 9/65/93, ESRC Transport Studies Unit, University College London, London. EIA, 2013, International Energy Outlook.
- Hobbs, B. (1991), "The 'most value' criterion: Economic evaluation of utility demand-side management programs considering consumer value", *The Energy Journal*, 12(2), 67-91.
- Holguín-Veras, J. and Thorson, E. (2003), "Modeling commercial vehicle empty trip with a first order trip chain model", *Transportation Research Part B: Methodological*, 37(2), 129-148.
- Hymel, K.M., Small, K.A. and Van Dender, K. (2010), "Induced demand and rebound effects in road transport", *Transportation Research Part B: Methodological*, 44(10), 1220-1241.
- IEA (2007), *Energy prices and taxes, Vol. 2006/4*, International Energy Agency, OECD Publishing, Paris.
- IEA (2014), *Energy prices and taxes, Vol. 2014/1*, International Energy Agency, Paris.
- IEA (2010), *Transport energy efficiency - Implementation of IEA recommendations since 2009 and next steps*, Technical report, International Energy Agency.

- IPCC (2014), *Mitigation of climate change: Contribution of working group III to the fifth assessment report of the Intergovernmental Panel on Climate Change*, Chapter 8, Cambridge University Press, Cambridge and New York.
- IRGC (2013), *The rebound effect: Implications of consumer behaviour for robust energy policies*, A review of the literature on the rebound effect in energy efficiency and report from expert workshops, Lausanne: International Risk Governance Council.
- Jägerbrand, A.K., Dickinson, J., Mellin, A., Viklund, M. and Dahlberg, S. (2014), *Rebound effects of energy efficiency measures in the transport sector in Sweden*, VTI Report 827A, The Swedish National Road and Transport Research Institute: Linköping, Sweden.
- Jenkins, J., Nordhaus, T. and Shellenberger, M. (2011), *Energy emergence: Rebound & backfire as emergent phenomena*, Oakland, The Breakthrough Institute.
- Jevons, W.S. (1865), *The coal question: Can Britain survive?*, Republished by Macmillan, London, UK, 1906.
- Jondrow, J., Lovell, C.A.K., Materov, I.S. and Schmidt, P. (1982), “On the estimation of technical efficiency in the stochastic frontier production function model”, *Journal of Econometrics*, 19, 233-238.
- Khazzoom, J.D. (1980), “The economic implications of mandated efficiency in standards for household appliances”, *The Energy Journal*, 1(4), 21-40.
- Kumbhakar, S.C. (2011), “Estimation of production technology when the objective is to maximize return to the outlay”, *European Journal of Operational Research*, 208, 170-176.
- Léonardi, J. and Baumgartner, M. (2004), “CO₂ efficiency in road freight transportation: Status quo, measures and potential”, *Transportation Research Part D: Transport and Environment*, 9, 451-464.
- Limanond, T., Jomnonkwao, S. and Srikaew, A. (2011), “Projection of future transport energy demand of Thailand”, *Energy Policy*, 39, 2754-2763.
- Llorca, M., Baños, J., Somoza, J. and Arbués, P. (2017). “A stochastic frontier analysis approach for estimating energy demand and efficiency in the transport sector of Latin America and the Caribbean”, *The Energy Journal*, 38(5), 153-174.
- Lundgren, T., Marklund, P.-O. and Zhang, S. (2016), “Industrial energy demand and energy efficiency – Evidence from Sweden”, *Resource and Energy Economics*, 43, 130-152.
- Maxwell, D., Owen, P., McAndrew, L., Muehmel, K. and Neubauer, A. (2011), *Addressing the rebound effect*, A report for the European Commission DG Environment, 26 April 2011.
- Matos, F.J.F. and Silva, F.J.F. (2011), “The rebound effect on road freight transport: Empirical evidence from Portugal”, *Energy Policy*, 39, 2833-2841.

- McKinnon, A.C. (2015), Environmental sustainability: A new priority for logistics managers, in A.C. McKinnon, M. Browne, A. Whiteing and M. Piecyk (eds.), *Green logistics: Improving the environmental sustainability of logistics*, Kogan Page, 3-31.
- Momenta (2006), *LCV scoping study – Phase 1: Review of published literature*, Report to Department for Transport.
- Mork, K.A. (1989), “Oil and macroeconomy when prices go up and down: An extension of Hamilton’s results”, *Journal of Political Economy*, 97(3), 740-744.
- Orea, L., Llorca, M. and Filippini, M. (2015), “A new approach to measuring the rebound effect associated to energy efficiency improvements: An application to the US residential energy demand”, *Energy Economics*, 49, 599-609.
- Piecyk, M. and McKinnon, A.C. (2010), “Forecasting the carbon footprint of road freight transport in 2020”, *International Journal of Production Economics*, 128, 31-42.
- Ruzzenenti, F. and Basosi, R. (2008), “The rebound effect: An evolutionary perspective”, *Ecological Economics*, 67, 526-537.
- Saunders, H.D. (1992), “The Khazzoom–Brookes postulate and neoclassical growth”, *The Energy Journal*, 13(4), 130-148.
- Saunders, H.D. (2000), “A view from the macro side: Rebound, backfire, and Khazzoom-Brookes”, *Energy Policy*, 28, 439-449.
- Saunders, H.D. (2008), “Fuel conserving (and using) production functions”, *Energy Economics*, 30, 2184-2235.
- Small, K.A. and Van Dender, K., (2007), “Fuel efficiency and motor vehicle travel: The declining rebound effect”, *The Energy Journal*, 28(1), 25-51.
- Sorrell, S. (2007), *The rebound effect: An assessment of the evidence for economy-wide energy savings from improved energy efficiency*, UK Energy Research Centre.
- Sorrell, S. and Dimitropoulos, J. (2008), “The rebound effect: Microeconomic definitions, limitations and extensions”, *Ecological Economics*, 65(3), 636-649.
- Sorrell, S., Dimitropoulos, J. and Sommerville, M. (2009), “Empirical estimates of the direct rebound effect: A review”, *Energy Policy*, 37, 1356-1371.
- Suganthi, L. and Samuel, A.A. (2012), “Energy models for demand forecasting—A review”, *Renewable and Sustainable Energy Reviews*, 16(2), 1223-1240.
- Szulc, B. (1964), “Indices for multiregional comparisons”, *Przegląd Statystyczny (Statistical Review)*, 3, 239-54.
- Tsamboulas, D., Vrenken, H. and Lekka, A-M. (2007), “Assessment of a transport policy potential for intermodal mode shift on a European scale”, *Transportation Research Part A: Policy and Practice*, 41, 715-733.
- Wadud, Z. (2016), “Diesel demand in the road freight sector in the UK: Estimates for different vehicle types”, *Applied Energy*, 165, 849-857.

- Walnum, H.J., Aall, C. and Løkke, S. (2014), “Can rebound effects explain why sustainable mobility has not been achieved?”, *Sustainability*, 6, 9510-9537.
- Wang, Z. and Lu, M. (2014), “An empirical study of direct rebound effect for road freight transport in China”, *Applied Energy*, 133, 274-281.
- Winebrake, J.J., Green, E.H., Comer, B. Corbett, J.J. and Froman, S. (2012), “Estimating the direct rebound effect for on-road freight transportation”, *Energy Policy*, 48, 252-259.
- Winebrake, J.J., Green, E.H., Comer, B., Li, C., Froman, S. and Shelby, M., (2015a), “Fuel price elasticities for single-unit truck operations in the United States”, *Transportation Research Part D: Transport and Environment*, 38, 178-187.
- Winebrake, J.J., Green, E.H., Comer, B., Li, C., Froman, S. and Shelby, M. (2015b), “Fuel price elasticities in the U.S. combination trucking sector”, *Transportation Research Part D: Transport and Environment*, 38, 166-177.